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Introducing Structural Considerations into Complexity Metrics

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Abstract

Field observations and focused interviews of Air Traffic Controllers have been used to generate a list of key complexity factors in Air Traffic Control. The underlying structure of the airspace was identified as relevant in many of the factors. A preliminary investigation has revealed that the structure appears to form the basis for abstractions that reduce the difficulty of maintaining Situational Awareness, particularly the projection of future traffic situations. Three examples of such abstractions were identified: standard flows, groupings, and critical points. Preliminary approaches to developing metrics including these structural considerations are discussed.

Introduction

In the face of the continued increase in demand for Air Traffic Control (ATC) services, there is a clear need for a better understanding of the capacity of airspace. At present, sector capacity is normally expressed as a maximum instantaneous number of aircraft in a sector. However, anecdotal evidence and direct observations suggest that this maximum capacity level varies between sectors and varies with different traffic situations.

In this paper it is assumed that complexity is related to the cognitive difficulty of controlling the air traffic situation, which in turn is tied to the ability of controllers to maintain safe operations under normal and abnormal conditions. The objective is to understand those factors that influence complexity, particularly those factors which relate to the underlying structural elements in ATC. Various structural elements and the mechanisms by which they reduce complexity have been identified. Including their effects in complexity metrics is an important step towards developing useful measures of complexity in ATC.

Improved measures of ATC complexity would find many applications including: airspace design, airspace slot allocation and traffic flow management. Specifically, such measures can be used to compare the effectiveness of different airspace structures, and/or to evaluate new air traffic management concepts.

Previous Work on ATC Complexity

Significant research interest in the concept of ATC complexity was generated by the “Free Flight” operational concept. Integral to Free Flight was the notion of dynamic density. Conceptually, dynamic density is a measure of ATC complexity that would be used to define situations that were so complex that centralized control was required [1].

Efforts to define “dynamic density” have identified the importance of a wide range of potential complexity factors, including structural considerations. However, the proposed complexity metrics have typically concentrated on only those factors that can be easily elicited from the geometry of an ATC situation [2], [3], [4], [5]. Examples of such geometric factors include aircraft densities, the proportion of aircraft maneuvering and encounter probabilities.

A few previous studies have attempted to include structural considerations in complexity metrics, but have done so only to a restricted degree. The Wyndemere Corporation proposed a metric that included one term that was based on the relationship between aircraft headings and a dominant geometric axis in a sector [5]. Including structural considerations has also been identified in recent work at Eurocontrol. In a study to identify complexity factors using expert judgment analysis, "Airspace Design" was identified as the second most important factor behind traffic volume [6].

Methodology

In order to investigate the relationship between structure and cognitive complexity, a series of site visits to ATC facilities in the United States, Canada and France were conducted. The site visits included both en-route and terminal area control centers.

The site visits consisted of focused interviews with current controllers and observations of live operations. To understand how complexity is regulated through traffic management initiatives, discussions were held with members of Traffic Management Units (TMU). Training personnel were interviewed to determine the importance of structure in the job training process.

Additionally, representative traffic patterns were captured using a commercial software product that provides a real-time feed of the Enhanced Traffic Management System (ETMS) data-stream.[1] This tool allows visualization of structural elements in the current system. It has also been used to generate illustrations of the use of that structure to reduce complexity.

Key Complexity Factors

Based on the field observations, ETMS data analysis, and a review of the pertinent literature, a list of the key factors influencing cognitive complexity was developed and is presented in Table 1. Factors that appear to relate to the underlying structure are identified by an asterix (*). No attempt has been made to rank the factors. However, they have been found to fall into three categories: *Airspace Factors*, *Traffic Factors*, and *Operational Constraints*.

Airspace Factors are those factors related to properties of the airspace. Represented are both internal properties, such as the distribution of navigational aids, and external properties, such as sector shape and coordination activities. In general, these factors are quasi-static, characterizing the underlying context within which a traffic load exists.

A second category, *Traffic Factors,* are factors dependent on the instantaneous distribution of traffic. They represent more dynamic and transient effects than *Airspace Factors*. Most previous efforts focused on measures associated with *Traffic Factors*.

Finally, *Operational Constraints* are additional operational requirements that placed restrictions on possible control actions. These factors tend to represent short-term or temporary variations in operational conditions.

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[1] It must be cautioned that the ETMS data was filtered by the provider to remove military and other potentially sensitive aircraft, and thus may under represent the real traffic situation.

*Table 1. Key factors reported by controllers as influencing cognitive complexity. Items marked with a * are related to structural elements.*

AIRSPACE FACTORS
Sector dimensions* *Shape* *Physical size* *Effective "Area of regard"*
Spatial distribution of airways / Navigational aids*
Number and position of standard ingress / egress points*
Standard flows* *Number of* *Orientation relative to sector shape* *Trajectory complexity* *Interactions between flows (crossing points, merges)*
Coordination with other controllers* *Point-outs* *Hand-offs*
TRAFFIC FACTORS
Density of aircraft *Clustering** *Sector-wide*
Aircraft encounters *Number of* *Distance between aircraft* *Relative speed between aircraft* *Location of point of closest approach (near airspace boundary, merge points etc…)** *Difficulty in identifying* *Sensitivity to controller's actions*
Ranges of aircraft performance *Aircraft types (747, Cessna)* *Pilot abilities*
Number of aircraft in transition *Altitude* *Heading* *Speed*
Sector transit time*
OPERATIONAL CONSTRAINTS
Buffering capacity*
Restrictions on available airspace *Presence of convective weather* *Activation of special use airspace** *Aircraft in holding patterns**
Procedural restrictions *Noise abatement procedures** *Traffic management restrictions (e.g. miles-in-trail requirements)*
Communication limitations

One important observation from the field studies is shown in Figure 1. A distinction was identified between the physical dimensions of a sector, the "Area of Responsibility," and the "Area of Regard" over which a controller's attention was focused. Events occurring near or outside the boundaries of a controller's sector are important for decisions about aircraft within the current sector. In the field observations, controllers often spent as much attention on incoming aircraft and their impact on the sector than on active aircraft in their sector.

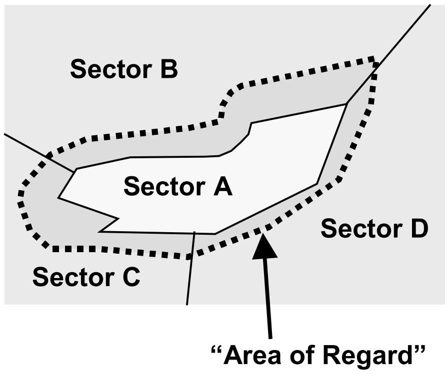

Figure 1. Dashed line demonstrates how the "Area of Regard" extends beyond the physical boundaries of Sector A.

Generalized Model of Complexity and Structure

Based on the field observations and analysis, structure appears to be used as the basis for abstractions that simplify the control process for controllers. Figure 2 shows a generalized model of how structure appears to influence the control process. The underlying structure, which influences the traffic situation can, if recognized, act as the basis for a set of abstractions internal to the controller that can simplify the task of predicting the future behavior of the traffic.

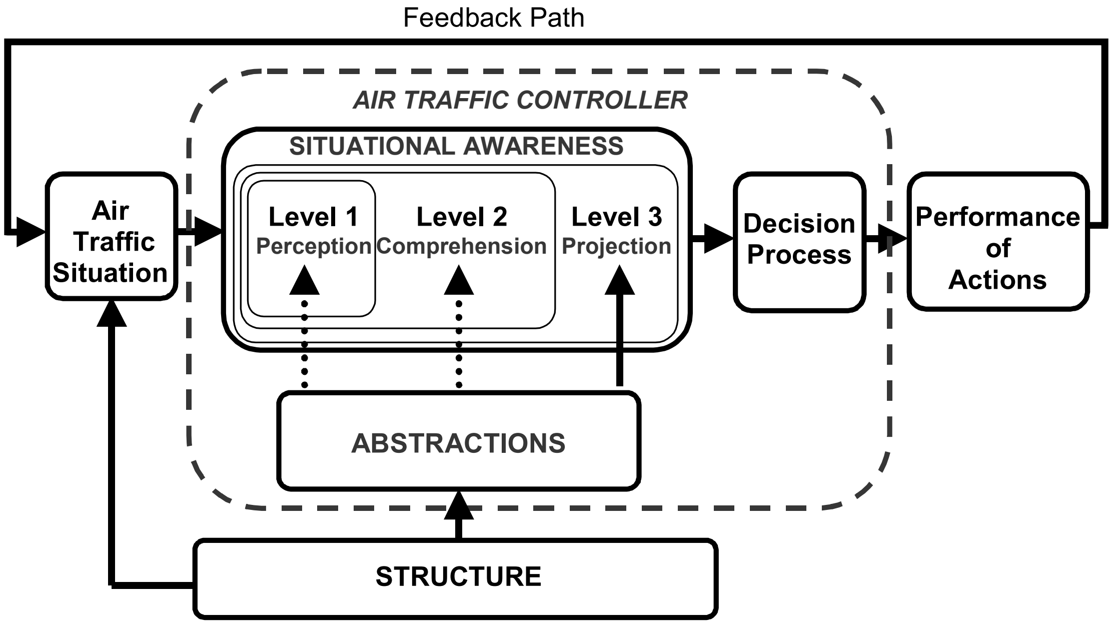

Figure 2. Proposed model illustrating how structure forms the basis for abstractions that influence Situational Awareness. (Adapted from [7]).

The abstractions are thought to support the controller's situational awareness at each of the three levels identified by Endsley: perception, comprehension, and projection [7]. The controller's ability to correctly project future traffic situations is essential to the decision making process. The key structure-based abstractions that have been identified each simplify the task of projecting future states of the traffic situation.

Several mechanisms have been identified. One such mechanism is the consolidation of the information required to project an aircraft's future path. Structure-based abstractions also simplify the task of identifying traffic conflicts by eliminating some potential interactions or by identifying areas of traffic focus. This limits the number of spatial locations at which interactions are likely to occur and eases the monitoring task.

It is hypothesized that controllers also use structure-based abstractions to simplify the decision process, and to reduce the complexity associated with the implementation of control actions. However, the remainder of this paper will focus on examples of structure-based abstractions reducing the cognitive difficulty associated with projecting future traffic situations.

Examples of Structure-Based Complexity Reduction Mechanisms

This preliminary investigation has identified three key structure-based abstractions that appear to reduce cognitive complexity in ATC. The key abstractions are:

- Standard Flows
- Groupings
- Critical Points

Each abstraction is described briefly below.

Standard Flows

Standard flows appear to be the most important structure-based abstraction used by controllers. There appear to be two structural bases that establish standard flows:

- Explicit structural elements
- Standardized operations

The first type of standard flow is based on explicit structural elements in the airspace system such as navigational aids, airways, and standardized procedures. An example of this type of flow is an arrival stream, as shown in Figure 3 for arrivals into Chicago from the East.

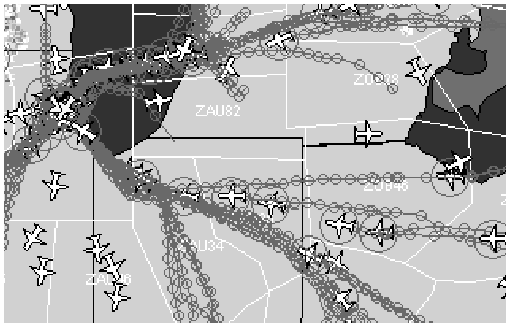

Figure 3. Example of standard arrival flows into O'Hare airport in Chicago.

The second type of standard flow emerges as a result of common practices, or standardized but unpublished patterns of operation. An example is the typical "trombone" vectoring sequence used to merge aircraft onto final approach.

An aircraft identified as a member of a flow carries with it an associated set of higher-level attributes such as expected future routing, ingress and egress points from the airspace, and locations of probable encounters. These attributes form a generalized expectation of an aircraft's trajectory through the airspace.

The standard flow abstraction emerges as a means of classifying aircraft into standard and non-standard classes on the basis of their membership in established flow patterns in a sector (see Figure 4). The task of projecting the future behavior of an aircraft that belongs to a standard flow is greatly simplified by the generalized expectation of its trajectory. In contrast, aircraft that are operating in ways that do not fall into the normal operating pattern, such as the "special case" aircraft in Figure 4, do not provide the same simplifications.

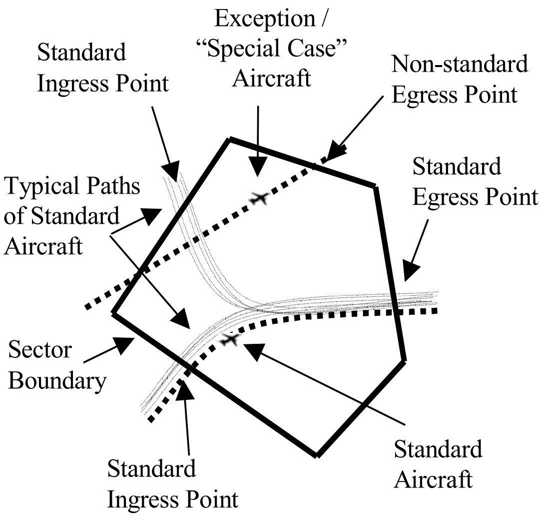

Figure 4. Standard flows form the basis for a structure-based abstraction, which distinguishes between standard and non-standard aircraft.

The standard flow abstraction accounts for the contextual nature of ATC. Snapshots of the instantaneous traffic situation do not capture all of the information that is available and used by controllers to understand and project the current traffic situation. Multiple aircraft do not need to be in the airspace to constitute a flow. Even if there is only a single aircraft currently following the flow path, the standard flow abstraction is still available.

Groupings

The presence of an underlying structure in a piece of airspace provides the basis for creating groups of aircraft linked by common properties. This type of abstraction can take advantage of properties that are known to segregate a traffic situation into non- or minimally-interacting groups.[2] Consequently, the

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[2] "Interactions" are not limited to solely aircraft-aircraft encounters, but can also include aircraft-airspace and aircraft-weather etc.

aircraft groups can be independently projected, reducing the cognitive complexity.

One simple example of a grouping abstraction is the standard flight levels that associate directions of travel with particular flight levels. This allows controllers to manage each flight level independently with vertically transitioning aircraft representing special cases.

As reported in Table 1, controllers have consistently reported altitude transitions as a key complexity factor [3], [4], [5], [6]. Aircraft that are transitioning between flight levels do not fit into the grouping abstraction, preventing a controller from projecting flight levels independently.

Grouping abstractions also explain an interesting result from the list of complexity factors in Table 1. Ranges of aircraft performance were identified as key factors influencing complexity. If aircraft performance was uniform, grouping abstractions could be used to simplify the projection task. For example, a wide distribution of aircraft speeds makes the process of projecting future positions more difficult than the case where all aircraft are flying at a uniform speed.

The grouping abstraction can also operate on the basis of the simple proximity of aircraft. Multiple examples of aircraft diverting as groups around convective weather have been observed. For example Figure 5 shows three distinct clusters of aircraft deviating as groups around convective activity.

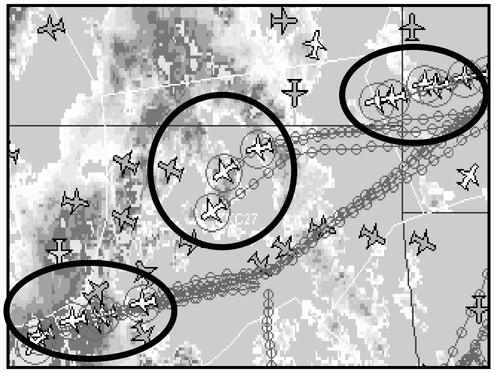

Figure 5. Example of clusters of aircraft following common paths while diverting around convective weather.

Critical Points

Critical points are an additional example of a structure-based abstraction that simplifies the projection task. The underlying structure, in the form of crossing and merge points of flows, will tend to concentrate the occurrences of encounters at common locations. A "critical point" abstraction can be formed from the standard responses to such encounters at the spatial locations.

Concentrating the location of aircraft encounters at a finite set of spatially localized points simplifies the analysis of a traffic situation. The dimensions of the spatial region that must be searched are reduced to a limited set of points. In forming projections, a controller's attention can be focused on a finite number of critical locations, simplifying the task.

Additionally, the typical responses associated with each critical point reduce the amount of cognitive effort that must be expended in evaluating encounters at the point. For example, the interaction between two aircraft approaching a merge point is reduced to a temporal or phasing problem. The same encounter geometry in the absence of a known critical point abstraction may require consideration of multiple dimensions, making the projection task more difficult.

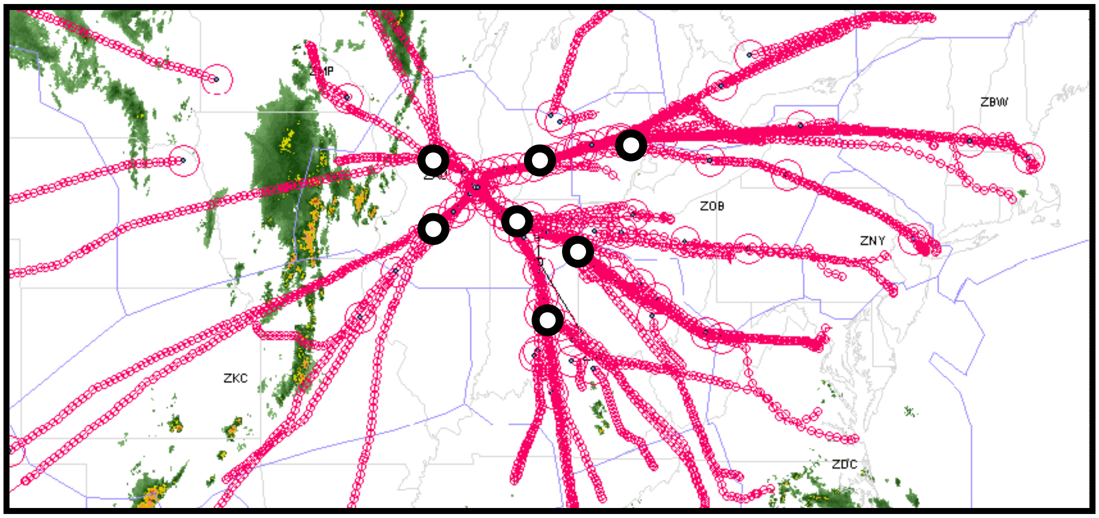

Figure 6. White dots are examples of critical points in the standard arrival flows into O'Hare airport in Chicago.

An example of a localized critical point is the merge point in an arrival stream. This can be seen in Figure 6, which shows the arrival flows into Chicago on May 3, 2001 at 9:00 p.m. The figure indicates that the merges occur at relatively well-defined spatial locations.

Robustness of Structure-Based Abstractions to Off-Nominal Conditions

Each of the structure-based abstractions identified above reduces cognitive complexity by simplifying the task of projecting future traffic situations. In general, abstractions take advantage of expectations created during operations under normal conditions. However, controllers must be able to guarantee safe operation of the system under both normal *and* abnormal conditions. The robustness of an abstraction will determine how effective that abstraction can be as a traffic system deviates from nominal conditions.

Structure-based abstractions can continue to function under some degree of system perturbation. For example, a standard flow abstraction may tolerate a localized disturbance in the flow trajectory, such as a deviation around an isolated area of convective weather. However, disturbances may become so large that the underlying structure can no longer be used to support the standard flow abstraction. Under such conditions, the cognitive complexity will increase dramatically; controllers sometimes report this as a fear of losing "the picture."

Including Structure-based Abstractions in Complexity Metrics

The identified structure-based abstractions motivate a variety of mathematical representations of cognitive difficulty. Three preliminary approaches to including structural considerations have been developed. Although none of the approaches have been fully developed, they represent examples of how structural considerations may be accounted for in metrics of cognitive complexity.

Explicit inclusion of Structural Elements

Given validated models of how structural elements influence complexity, they could be explicitly included in a metric. If, for example, critical points were identified as being a key part of a mechanism, then it would be possible to include an explicit term in a complexity metric based on the number of merge points in a sector. Such an approach is dependent on developing a prior understanding of the relative effects of the structure.

The standard flow abstraction identified above suggests that the cognitive difficulty of handling an aircraft that is on a standard flow is reduced compared with a non-standard aircraft. Within a complexity metric, aircraft can be classified as standard or non-standard based on a comparison between their position, velocity, and destination and a known set of standard flows for the sector.

Situational Measures of Complexity: Cluster Approach

The grouping abstraction motivates a second approach to a complexity metric. Delahaye and Puechmorel introduced three geometrical metrics: proximity, convergence and insensitivity, which aim to capture respectively the level of aggregation of aircraft, the convergences in sectors and the difficulty in solving the induced conflicts [2]. G. Aigoin has extended and refined these concepts using a cluster-based analysis [8].

Two aircraft are said to be in the same cluster if the product of their relative speed and their proximity (a function of the inverse of the relative distance) is above a threshold. For each cluster, a matrix of relative dependence between aircraft is computed and the whole complexity of the cluster is then given by a weighted sum of some matrix norm. Those norms give an aggregated measure of the level of proximity of aircraft in clusters and the associated convergence with the relative speed. From the cluster matrix it is also possible to compute the difficulty of the cluster. The difficulty captures how hard it is to solve this cluster.

Multiple clusters can exist within a sector, and their interactions must also be taken into account (see Figure 7). A measure of this interaction has been proposed by G. Aigoin [8]. This technique allows multiple metrics of complexity to be developed such as average cluster complexity, maximum and minimum cluster complexities, and complexity speeds.

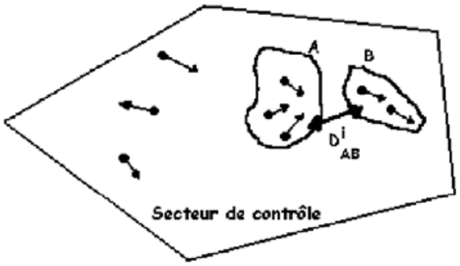

Figure 7. A cluster based analysis considers both *intra* and *inter* cluster complexities.

Kolmogorov Entropy Metrics: Structure Through Trajectory Disorder

Where the previous approach used clusters to parse aircraft states, an alternative mathematical representation has been developed based on measures of disorder of aircraft trajectories. The use of standard flows points to the importance of the distribution of aircraft trajectories within a sector. Specifically, measures of the disorder of trajectories in a sector will reflect the degree to which standard flows are being used and hence provide a proxy estimate of the cognitive difficulty

In generating such measures, the classical probabilistic entropy is not relevant because the number of aircraft in a sector is too small to give accurate estimates of the associated statistic. However, topologic entropy (Kolmogorov entropy) is adapted to capture this disorder and works on the shape of trajectories.

The control sector is considered as a dynamical system for which the state space is the 3D geometrical space in which aircraft are flying. A 3D state space dynamical system cannot model the aircraft route because of ambiguity introduced by the presence of crossing aircraft trajectories. To circumvent such a limitation the state space has been extended to the fourth dimension (x,y,z,t) and locally to the fifth dimension in order to produce artificial trajectories without crossing. This local increasing of the dimension is needed only when a conflict appear and will be used to increase the associated complexity in the sector.

The results from dynamical system theory can be applied to this model. The metric works on trajectories themselves and not only on the associated speed vectors. Therefore, it uses the full evolution of aircraft in the past and can capture the intent information associated with a flight plan provided to the model. For a given time window (this window is a parameter given to the model), the Kolmogorov Entropy is computed for each time step belonging to this window. If the necessary intent information is not available the model will do a linear extension of trajectories.

When the predictor is linear, the traffic is assumed to be routed on direct routes. From this direct routing the "natural" complexity of the demand without any action of the air traffic system can be observed. This approach can be used to estimate the impact of the geographical/temporal distribution of the demand on the complexity.

Conclusions

Understanding cognitive complexity is an important component of ensuring safe and efficient use of airspace. Based on complexity factors reported by controllers, structure appears to form the basis for abstractions that reduce the difficulty of maintaining situational awareness.

In this preliminary study, three key abstractions have been identified:

- Standard Flows
- Groupings
- Critical Points

These structure-based abstractions appear to play important roles in reducing the difficulty of projecting the future behavior of traffic situations. Not including the underlying structural elements on which these abstractions are based may artificially inflate the outputs of any cognitive complexity metrics. Three preliminary approaches to including structural considerations in complexity metrics have been discussed.

Author Biographies

Jonathan Histon is a Masters student in the International Center for Air Transportation of the Department of Aeronautics & Astronautics at MIT. He obtained a B.Sc. (Honours Physics) in 2000 from Simon Fraser University, Canada. His main research interests are metrics of complexity, human factors in ATC, and safety in ATC.

Guillaume Aigoin is an engineer graduated from the ENAC (Civil Aviation National School), having received his master Degree in Automatic Control from the LAAS Laboratory (Laboratoire d'Automatique et d'Analyse des Systemes) in 2001. His Master thesis dissertation focuses on the development of new complexity metrics for air traffic management systems.

Daniel Delahaye is a faculty member of the Global Optimization Laboratory of CENA since 1996. He is member of the artificial evolution team of the applied math research center (CMAP: Polytechnique school). He obtained his engineer degree from the ENAC school and did a master of science in signal processing from the national polytechnic institute of Toulouse in 1991. His obtained his PH.D in automatic control from the aeronautic and space national school in 1995 and did a post-doc at the Department of Aeronautics & Astronautics at MIT in 1996. He conducts research on airspace design and traffic assignment in order to reduce the congestion in sector.

R. John Hansman has been on the faculty of the Department of Aeronautics & Astronautics at MIT since 1982. He obtained his A.B. in Physics from Cornell University in 1976, his S.M. in Physics in 1980 and his Ph.D. in Physics, Meteorology, Aeronautics & Astronautics and Electrical Engineering from MIT in 1982. He is the Head of the Humans and Automation Division, the Director of the International Center for Air Transportation and of the Aeronautical Systems Laboratory at MIT. He conducts research in several areas related to flight vehicle operations and aviation safety. His current research activities focus on advanced cockpit information systems, including Flight Management Systems, air-ground datalink, electronic charting, advanced alerting systems, and flight crew situational awareness, cockpit human factors and information management.

Stephane Puechmorel is a research associate at the Math department of the Enac school. He graduated from the Polytechnique school and obtained his master degree in signal processing in 1990 and his Ph.D in pure math in 1992 from the national polytechnic institute of Toulouse. He conducts research on algebraic topology and infers new models for air traffic complexity.

References

[1] RTCA, Final Report of RTCA Task Force 3: Free Flight Implementation, RTCA Inc. October 1995.

[2] Delahaye, D. and Puechmorel, S., Air Traffic Complexity: Towards Intrinsic Metrics, 3rd USA/Europe Air Traffic Management R&D Seminar (Napoli), 2000.

[3] Laudeman et al. Dynamic Density: An Air Traffic Management Metric, NASA-TM-1998-112226, April 1998.

[4] Sridhar, B., Seth, K.S., Grabbe, S. Airspace Complexity and its Application in Air Traffic Management, 2nd USA/Europe Air Traffic Management R&D Seminar (Orlando), 1998.

[5] Wyndemere Inc., An Evaluation of Air Traffic Control Complexity, Final Report (NASA 2-14284), October 1996.

[6] Kirwan, B., Scaife, R., Kennedy, R. Investigating Complexity Factors in U.K. Air Traffic Management, Human Factors and Aerospace Safety, Volume 1 (#2), June 2001.

[7] Endsley, M, Rodgers, M., Situational Awareness Requirements for En-route Air Traffic Control, DOT/FAA/AM-94/27, December 1994.

[8] Aigoin, G. Air Traffic Complexity Modeling, Master Thesis. ENAC. 2001